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Influence of Steam Recovery and Consumption on Energy Consumption per Ton of Steel

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Abstract

Steam recovery and consumption contributes greatly to energy consumption per ton of steel. It is studied in this paper that the relationship between energy consumption per ton of steel and steam recovery & consumption, including main processes, auxiliary processes, diffusion and other users, respectively. And the factors attributing to energy consumption per ton of steel is analyzed. The expressions of steam consumption per ton of steel and energy consumption per steam supply are proposed in this paper.

Keywords: energy consumption per ton of steel; steam recovery; steam consumption; energy consumption per steam supply

Nomenclature

b	energy consumption per steam supply	n	number of main processes
B	energy consumption from exergy loss	n_a	number of auxiliary processes
D	demand of steam	n_k	number of boilers and generator sets
E	energy consumption per ton of steel	P	steel production
Ex	exergy	p	product – steel ratio
e	energy consumption per ton of product	T_0	environment temperature
e_x	specific exergy	η	exergy efficiency
m	number of steam supply links	η_{ex}	conversion efficiency / loss efficiency

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Subscripts

aux	auxiliary process	gs	generator set
dif	energy diffusion	i	i-th process
els	energy consumers expect pro, aux and dif	pro	main process
gl	boiler	r	r-th boiler or generator set

Superscripts

con	consumption of energy or steam	rb	boiler driven by residual heat
f	fuel	rec	recovery of energy or steam
fb	boiler driven by fuel	rel	steam release
loss	steam loss in pipeline transporting	st	steam
oth	other energies except steam		

1. Introduction

In the process of iron- and steel-making, energy consumption is usually occurred while a mass of secondary energy is emerged, among which steam is one of the main energies. Energy consumption per ton of steel is used in iron and steel industry to evaluate the energy consumption [1]. It is defined as the rate of total energy consumption to the output of steel in statistical period. Steam consumption accounts for around 10% of total energy consumption in an iron and steel enterprise [2]. The energy consumption and running cost can be saved by improving the recovery and utilization of steam. However, many researchers are paying more attentions to the optimized utilization of by-product gas [3, 4] than that of steam. To analyze the influence of steam recovery and consumption on energy consumption per ton of steel, some relational expressions are given in this paper. Like the evaluating index of consumption of all kinds of energies, the evaluating index is selected as steam consumption per ton of steel whose influencing factors are also studied in this paper.

2. Relationship between energy consumption per ton of steel and steam recovery & consumption

Energy consumption per ton of steel (E) can be divided into four parts: energy consumption by main processes (E_{pro}), energy consumption by auxiliary processes (E_{aux}), energy diffusion (E_{dif}) and energy consumption by other users (E_{els}). The expression is

$$E = E_{\text{pro}} + E_{\text{aux}} + E_{\text{dif}} + E_{\text{els}} \tag{1}$$

2.1. Energy consumption by main processes

E_{pro} is expressed as

$$E_{\text{pro}} = \sum_{i=1}^{n} \left(e_i \cdot p_i\right) \tag{2}$$

where e_i can be calculated as

$$e_i = e_i^{\text{con}} - e_i^{\text{rec}} \tag{3}$$

To study the influences of consumption and recovery of steam, they are listed separately in Eq. (3) as follows:

$$e_i = \left(e_i^{\text{con, st}} - e_i^{\text{rec, st}}\right) + \left(e_i^{\text{con, oth}} - e_i^{\text{rec, oth}}\right) \tag{4}$$

Then E_{pro} can be expressed as

$$E_{\text{pro}} = \sum_{i=1}^{n} \left[\left(e_i^{\text{con, st}} \cdot p_i - e_i^{\text{rec, st}} \cdot p_i \right) + \left(e_i^{\text{con, oth}} \cdot p_i - e_i^{\text{rec, oth}} \cdot p_i \right) \right] \tag{5}$$

It can be found from Eq. (5) that there are two methods to reduce E_{pro} for steam: one is reducing steam consumption and/or increasing steam recovery, the other is reducing the product – steel ratio.

2.2. Energy consumption by auxiliary processes

Auxiliary processes in iron and steel enterprise consist of power generation, oxygen making, feed water, etc. As the products of power generation process are steam and electricity, it is a special process labeled as (n+1)-th process. Other auxiliary processes are named from process (n+2). The expression of E_{aux} is written as

$$E_{\text{aux}} = \sum_{r=1}^{n_k} \left[e_r^{\text{con}} \left(1 - \eta_r^{\text{gl}} \left(1 - \eta_r^{\text{gs}}\right)\right) - e_r^{\text{rec, st}} \right] \cdot p_{n+1} + \sum_{i=n+2}^{n+n_a} \left[e_i^{\text{con, st}} \cdot p_i + \left(e_i^{\text{con, oth}} \cdot p_i - e_i^{\text{rec, oth}} \cdot p_i \right) \right] \tag{6}$$

From the view of recovery and consumption of steam, it can be found from Eq. (6) that the steam consumption of auxiliary processes should be reduced to reduce the energy consumption per ton of steel. Besides, the energy efficiency of boilers and thermal electricity conversion efficiency of generator sets should be increased, such as selecting high efficiency combined cycle power plant.

2.3. Energy diffusion

Energy diffusion is the energy loss caused by the imbalance of energy demand and energy supply of metallurgical process. It can be expressed as

$$E_{\text{dif}} = E_{\text{dif}}^{\text{st}} + E_{\text{dif}}^{\text{oth}} \tag{7}$$

For steam in iron and steel enterprise, its diffusion comes from two points. One is the loss from release. Steam produced should be immediately recovered and used because it is not easy to be stored. Moreover, due to the unbalanced supply – demand and the limitation of bulk users, the extra steam has to be released, which increases the energy consumption per ton of steel. The other is the loss from pipeline transporting. So steam should be transported by the minimum distance, the minimum pressure drop and the minimum heat loss. Then, Eq. (7) can be rewritten as

$$E_{\text{dif}} = \left(E_{\text{dif}}^{\text{st, rel}} + E_{\text{dif}}^{\text{st, loss}} \right) + E_{\text{dif}}^{\text{oth}} = \sum_{i=1}^{n+n_a} \left(e_i^{\text{rec, st}} \eta_i^{\text{rel}} p_i + e_i^{\text{rec, st}} \eta_i^{\text{loss}} p_i \right) + E_{\text{dif}}^{\text{oth}} \tag{8}$$

2.4. Energy consumption by other users

Energy consumption by other users contains energy consumptions of gas processing, steam locomotive, and material preparation, etc. It is usually constant and expressed as

$$E_{\text{els}} = E_{\text{els}}^{\text{st}} + E_{\text{els}}^{\text{oth}} \tag{9}$$

Based on the four aspects mentioned above, the influence of steam recovery and consumption on energy consumption per ton of steel can be gotten as

$$\Delta E = E_{\text{pro}}^{\text{st}} + E_{\text{aux}}^{\text{st}} - E_{\text{dif}}^{\text{st}} \tag{10}$$

According to Eqs. (1) to (10) the attribution of steam recovery and consumption to energy consumption per ton of steel is

$$\Delta E = \sum_{i=1}^{n}\left(e_i^{\text{rec, st}} \cdot p_i\right) + \sum_{r=1}^{n_k}\left[e_r^{\text{con}}\left(1-\eta_r^{\text{gl}}\left(1-\eta_r^{\text{gs}}\right)\right) - e_r^{\text{rec, st}}\right]\cdot p_{n+1} - \sum_{i=n+2}^{n+n_a}\left[e_i^{\text{rec, st}}\eta_i^{\text{rel}} p_i + e_i^{\text{rec, st}}\eta_i^{\text{loss}} p_i\right] \quad (11)$$

The first item of Eq. (11) presents the influence of steam recovery on energy consumption per ton of steel, the second item is the influence of boiler on energy consumption per ton of steel, and the third item is the influence of steam diffusion on energy consumption per ton of steel. All the factors can be presented in steam consumption per ton of steel and energy consumption per steam supply.

3. Influencing factors of attribution to energy consumption per ton of steel

3.1. Steam consumption per ton of steel

The expression of steam consumption per ton of steel is

$$p_i^{\text{st}} = D_i / P = \left(t_i^{\text{st, fb}} + t_i^{\text{st, rb}}\right)\left(1-\eta_i^{\text{rel}}\right)\left(1-\eta_i^{\text{loss}}\right)/P \quad (12)$$

It can be found from Eq. (12) that the demand of steam is the key factor influencing steam consumption per ton of steel. Therefore, the management of steam system should be enhanced to reduce the energy consumption per ton of steel. For a given demand of steam, energy conservation can be achieved by increasing steam recovery and/or reducing steam diffusion.

3.2. Energy consumption per steam supply

According to specific energy consumption theory [5, 6], the expression of energy consumption per steam supply is

$$b = e_x^{\text{st}} / e_x^{\text{f}} + \sum_{k=1}^{m} B_k \Big/ D = b_{\min} + \sum_{k=1}^{m} b_k \quad (13)$$

where, $\sum_{k=1}^{m} b_k$ is the sum of additional energy consumption derived from exergy loss in each links, $b_{\min}$ presents the minimum energy consumption for a given steam demand. For a given heat with the mean thermodynamic temperature of $\overline{T}_h$, then

$$b_{\min} = 34.4\left(1 - T_0 / \overline{T}_h\right) \quad (14)$$

As the additional energy consumption is caused by exergy loss, the additional energy consumption of k-th link is

$$b_k = b_{\min} \cdot \left[\left(Ex_{k+1} - Ex_k\right)/Ex_1\right] \quad (15)$$

Based on Eq. (15), the additional energy consumption of steam users of link 1 is

$$b_1 = b_{\min} \cdot \left[\left(Ex_2 - Ex_1\right)/Ex_1\right] = b_{\min} \cdot \left(1/\eta_{ex1} - 1\right) \quad (16)$$

The additional energy consumption of link 2 is

$$\begin{aligned} b_2 &= b_{\min} \cdot \left[\left(Ex_3 - Ex_2\right)/Ex_1\right] = \left(b_{\min} + b_1\right)\left[\left(Ex_3 - Ex_2\right)/Ex_2\right] \\ &= \left(b_{\min} + b_1\right)\cdot\left(1/\eta_{ex2} - 1\right) = \left[b_{\min} + b_{\min}\left(1/\eta_{ex1} - 1\right)\right]\cdot\left(1/\eta_{ex2} - 1\right) \\ &= b_{\min} \cdot \left(1/\eta_{ex1}\right)\cdot\left(1/\eta_{ex2} - 1\right) \end{aligned} \quad (17)$$

With the same regulation, the additional energy consumption of k-th link is

$$b_k = b_{\min} \cdot \left[\left(Ex_{k+1} - Ex_k \right) / Ex_1 \right] = \left(b_{\min} + \sum_{z=1}^{k-1} b_z \right) \left[\left(Ex_{k+1} - Ex_k \right) / Ex_k \right] = b_{\min} \cdot \prod_{z=1}^{k-1} \left(\frac{1}{\eta_z} \right) \cdot \left(\frac{1}{\eta_k} - 1 \right) \tag{18}$$

Then, the energy consumption per steam supply of total system can be expressed as

$$b = b_{\min} + \sum_{k=1}^{m} b_k = b_{\min} + b_{\min} \cdot \prod_{z=1}^{k-1} \left(1/\eta_z \right) \cdot \left(1/\eta_k - 1 \right) = b_{\min} \cdot \prod_{z=1}^{k} \left(1/\eta_z \right) \tag{19}$$

It is assumed that the exergy efficiency of k-th link of steam recovery and utilization system η_k is changed, resulting the change of exergy efficiencies of z ($z = k - q$, $1 \le q \le k$) links after it. Then the change of energy consumption per steam supply can be gotten according to Eq. (19), which is as follows

$$\begin{aligned} \Delta b &= \left(\frac{\partial b}{\partial \eta_k} \right) \Delta \eta_k + \left(\frac{\partial b}{\partial \eta_{k-1}} \right) \Delta \eta_{k-1} + \cdots + \left(\frac{\partial b}{\partial \eta_q} \right) \Delta \eta_q \\ &= -b_{\min} \cdot \prod_{z=k+1}^{m} \frac{1}{\eta_z} \cdot \prod_{z=1}^{q-1} \frac{1}{\eta_z} \cdot \left(\frac{1}{\eta_k^2} \cdot \frac{1}{\eta_{k-1}} \cdot \cdots \cdot \frac{1}{\eta_q} \Delta \eta_k + \cdots + \frac{1}{\eta_k} \cdot \frac{1}{\eta_{k-1}} \cdot \cdots \cdot \frac{1}{\eta_q^2} \Delta \eta_q \right) \end{aligned} \tag{20}$$

According to Eq. (18), the additional energy consumption of q-th link is

$$b_q = b_{\min} \cdot \prod_{z=1}^{q-1} \left(1/\eta_z \right) \cdot \left(1/\eta_q - 1 \right) \tag{21}$$

As the exergy efficiency of q-th link changes, differential Eq. (21) versus η_q, it arrives at

$$\frac{\partial b_q}{\partial \eta_q} = -b_{\min} \cdot \prod_{z=1}^{q-1} \frac{1}{\eta_z} \cdot \frac{1}{\eta_q^2} \tag{22}$$

Thus,

$$\Delta b_q = \frac{\partial b_q}{\partial \eta_q} \cdot \Delta \eta_q = -b_{\min} \cdot \prod_{z=1}^{q-1} \frac{1}{\eta_z} \cdot \frac{1}{\eta_q^2} \cdot \Delta \eta_q \tag{23}$$

Likewise,

$$\begin{aligned} \Delta b_k &= \frac{\partial b_{q+1}}{\partial \eta_q} \cdot \Delta \eta_q + \frac{\partial b_{q+1}}{\partial \eta_{q+1}} \cdot \Delta \eta_{q+1} + \cdots + \frac{\partial b_k}{\partial \eta_k} \cdot \Delta \eta_k \\ &= -b_{\min} \cdot \prod_{z=1}^{q-1} \frac{1}{\eta_z} \cdot \left(\frac{1}{\eta_k} - 1 \right) \cdot \frac{1}{\eta_{k-1}} \cdot \cdots \cdot \frac{1}{\eta_q^2} \cdot \Delta \eta_q - \cdots - b_{\min} \cdot \prod_{z=1}^{q-1} \frac{1}{\eta_z} \cdot \frac{1}{\eta_k^2} \cdot \frac{1}{\eta_{k-1}} \cdot \cdots \cdot \frac{1}{\eta_q} \cdot \Delta \eta_k \end{aligned} \tag{24}$$

Then,

$$\sum_{z=q}^{k} \Delta b_z = -b_{\min} \cdot \prod_{z=1}^{q-1} \frac{1}{\eta_z} \cdot \left(\frac{1}{\eta_k^2} \cdot \frac{1}{\eta_{k-1}} \cdot \cdots \cdot \frac{1}{\eta_q} \cdot \Delta \eta_k + \cdots + \frac{1}{\eta_k} \cdot \frac{1}{\eta_{k-1}} \cdot \cdots \cdot \frac{1}{\eta_q^2} \cdot \Delta \eta_q \right) \tag{25}$$

Dividing Eq. (20) by Eq. (25), then

$$\Delta b \Big/ \sum_{z=q}^{k} \Delta b_z = \prod_{z=k+1}^{m} \frac{1}{\eta_z} \tag{26}$$

It is drawn from Eq. (26) that the sum of additional energy consumption of all links whose exergy efficiency is changed and the total energy consumption per steam supply is a simply proportional relationship, and the proportionality coefficient is the reciprocal of product of exergy efficiencies unchanged.

4. Summary

Energy consumption per ton of steel has great relation to steam recovery and consumption. In this paper, the relationship between energy consumption per ton of steel and steam recovery & consumption is studied. It is indicated that steam recovery and consumption by main processes, steam recovery and consumption by auxiliary processes, steam diffusion and steam consumption by other users is the factors influencing the energy consumption per ton of steel. Steam consumption per ton of steel and energy consumption per steam supply are proposed. The demand of steam is the key factor influencing steam consumption per ton of steel. And the proportional relationship between the sum of additional energy consumption of all links whose exergy efficiency is changed and the total energy consumption per steam supply is concluded.

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